Laser Assisted RObotic Surgery of the anterior Eye Segment

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[1] Dissemination Level:

PU	Public
PP	Restricted to other programme participants (including the Commission Services)
RE	Restricted to a group specified by the consortium (including the Commission Services)
CO	Confidential, only for members of the consortium (including the Commission Services)

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4	5/10/2015	**Final**	**Fastenica**	**Final Revision**

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Introduction

This report describes the technical activities carried out during the development phase of the LA-ROSES Eye-hand-piece system control unit to accomplish the objective to provide control capabilities to be able the laser spot to follow the welding path and to be able to drive the laser powering output emission according to surgeon settings. Reports D2.1 and D3.4 are used as references. The Eye hand-piece is a complete and independent system that does not require to be attached to the mechanical arm to be driven. The mechanical arm is used to move the Eye hand-piece above the patient eye so that it can be positioned to a particular spatial location before starting the laser welding process. This preliminary positioning by using the robotic arm it is necessary because the Eye hand-piece system provides a limited range of motion to the laser tip; so it is necessary to calculate the relative positioning between the hand-piece and the welding trajectory described by the path marked by the indocyanine solution. The laser movement control unit here described is devoted to provide movement control capabilities to the laser tip only: i.e. circular, translational and orientation movements. The robotic arm control system to be used to move the whole eye hand-piece, the machine vision functionalities and other image processing algorithms, which are used to control and tune the positioning phase and the laser welding process, will be described in dedicated reports.

1 Eye hand-piece Control Unit

Based on the system architecture definition as shown in D2.1 we provide a list of motor and driver components and a system diagram scheme to show motor and electronic components of the eye hand-piece as it is presented and described in D3.4.

For sake of comprehensiveness below the system architecture and a 3D sketch of the eye hand-piece.

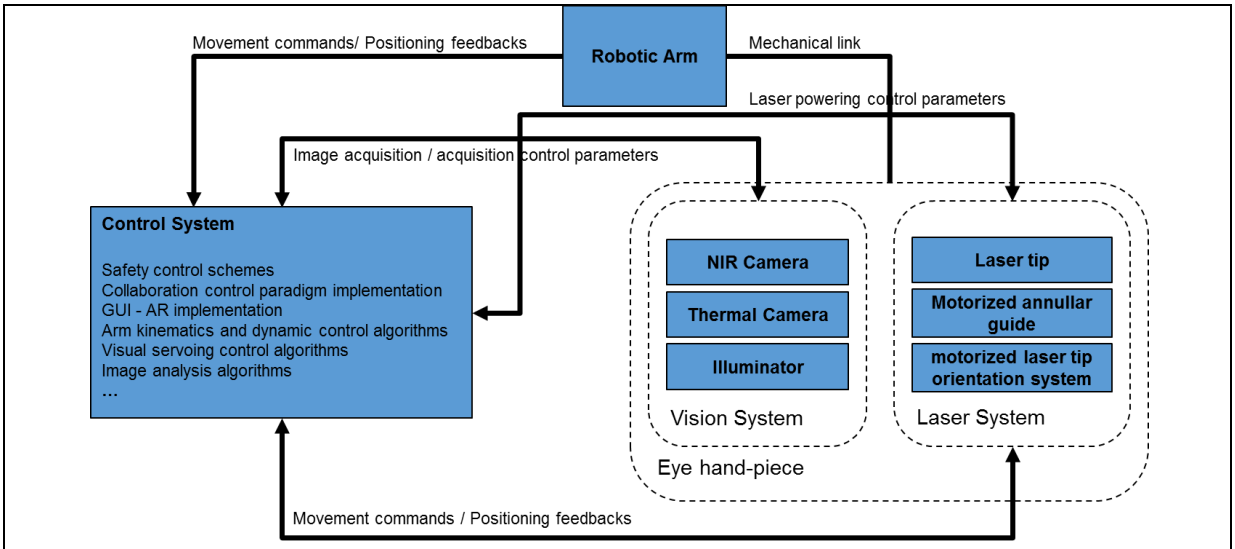


Fig. 1 – LA-ROSES overall system diagram. In this report the "Laser System" subsystem is explained.

In this report the subsystem denoted with "Laser System" has been considered. Also the physical devices used to realize the communications capabilities denoted with the arrow "Movement commands/ Positioning feedbacks" are pointed out and clarified.

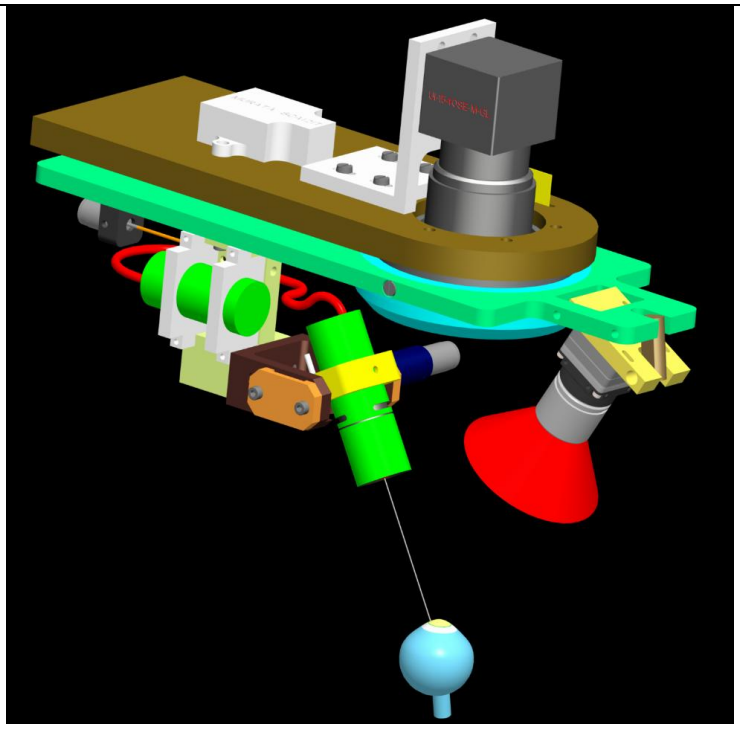


Fig. 2 – LA-ROSES 3D drawing of the Eye hand-piece. Laser movements and light powering emission are considered here.

1.1 Laser handling

The laser diode emitter we are going to use is composed of two parts; it has the power driver as a separate component so that the optical laser unit can be better arranged and driven by the handling unit. The LA-ROSES laser handling unit is composed of three motors which equips the Eye hand-piece.

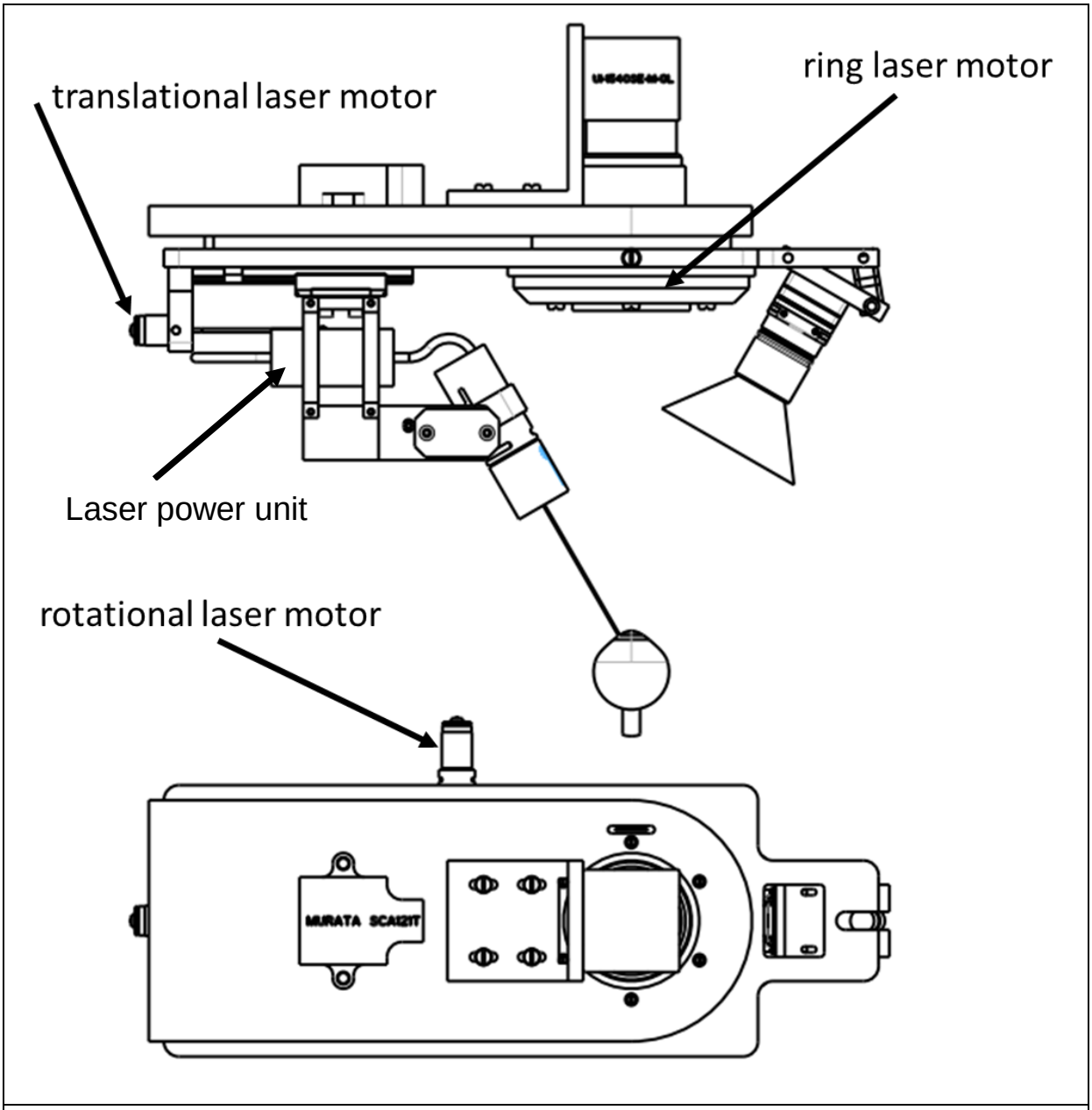


Fig. 3 – Laser tip handling system is highlighted.

According to designing requirements including masses, loads, inertial properties of each devices, dynamics and statics aspects the following motors have been chosen.

Motor type	Motor code identification
translational laser motor	FAULHABER ADM1220S
rotational laser motor	FAULHABER ADM1220S
ring laser motor	FAULHABER RDM66200

Technical specs of FAULHABER ADM1220S are the following.

FAULHABER

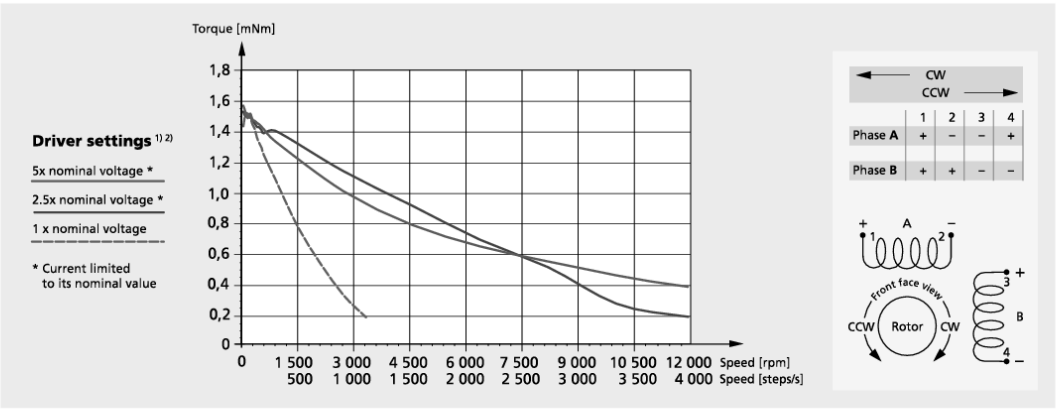
Stepper Motors 2,4 mNm

Two phase, 20 steps per revolution
microstepping motor (low residual torque), PRECIstep® Technology

ADM1220S-ww-ee

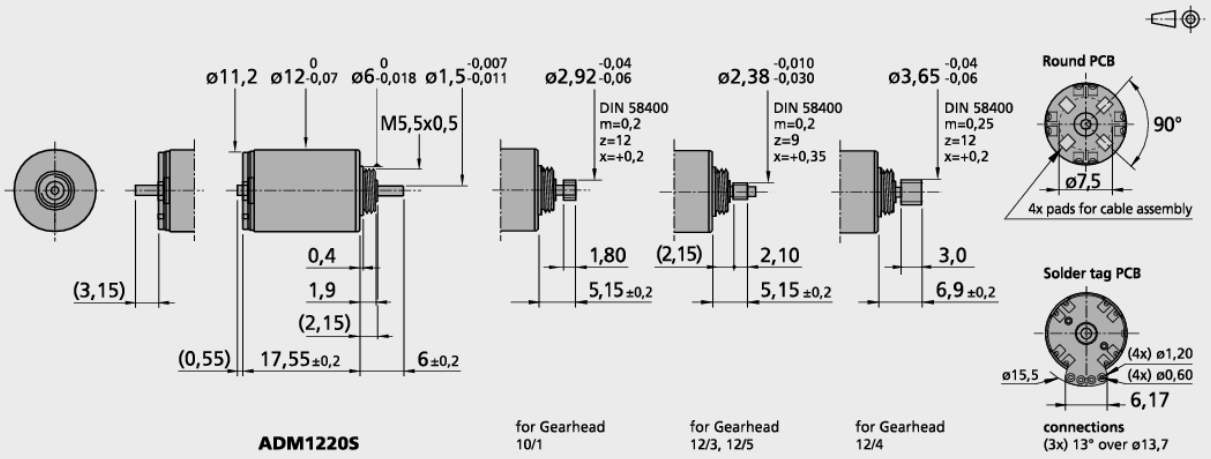
	ww =	V2		V3		V6		V12		
		Current	Voltage	Current	Voltage	Current	Voltage	Current	Voltage	Drive mode
1	Nominal current per phase (both phases ON) [1]	0,33	–	0,22	–	0,11	–	0,055	–	A
2	Nominal voltage per phase (both phases ON) [1]	–	2	–	3	–	6	–	12	V DC
3	Phase resistance (at 20°C)	4,5		10,4		41		168		Ω
4	Phase inductance (1kHz)	1,3		3,5		13		57		mH
5	Back-EMF amplitude	1,7		2,6		5,0		10,0		V/k step/s
6	Holding torque (at nominal current in both phases)	2,4								mNm
7	Holding torque (at twice the nominal current)	4,1								mNm
8	Step angle (full step)	18								degree
9	Angular accuracy [1]	± 3								% of full step
10	Residual torque, max.	0,15								mNm
11	Rotor inertia	18,5								$\cdot 10^{-9}$ kgm²
12	Resonance frequency (at no load)	128								Hz
13	Electrical time constant	0,28								ms
14	Ambient temperature range	–35 ... +70								°C
15	Winding temperature tolerated, max.	130								°C
16	Thermal resistance R_{th1} / R_{th2}	11,9 / 46,5								°C/W
17	Thermal time constant τ_{w1} / τ_{w2}	5 / 300								s
18	Shaft bearings	sintered bronze sleeves (standard)				ball bearings, preloaded (optional)				
19	Shaft load, max.:									
	– radial (3 mm from bearing)	0,5				6,0				N
	– axial	3,0				3,0				N
20	Shaft play, max.:									
	– radial (0,2N)	15				12				µm
	– axial (0,2N)	~0				~0				µm
21	Isolation test voltage	200								V DC
22	Mass	9								g

[1] Relevant for 2 phases ON only. On PWM drivers or chopper (current mode), the current is set to the nominal value and the supply voltage is typically 3 to 5x higher than the nominal voltage.
[2] Curves measured with a load inertia of 20 $\cdot 10^{-9}$ kgm², in half-step mode for the "1 x nominal voltage" curve, in 1/4 micro-stepping mode for the other curves.



For notes on technical data and lifetime performance refer to "Technical Information".
Edition 2015

Dimensional drawing



Combinations

Drive Electronics	Encoders	Cables	Gearheads / Lead screws
MCST3601		List available on request	**10/1** **12/3** **12/4** **12/5*** Lead screws **M2 - M2,5 - M3**

* Zero Backlash Gearheads

Ordering information

Example: **ADM1220S-2R-V2-51**

Motor type ADM = Motor design 12 = Motor diameter (mm) 20 = Steps per revolution	Bearings (rr) Special lubricant options available	Winding (ww)	Motor execution (ee) Only front output shaft	With double output shaft	Front output shaft
ADM1220S	- (sleeve bearings)	**-V2**	**-51** (Round PCB)	**-50** (Round PCB)	Plain shaft, plain shaft for lead screw M3
	-2R (2 ball bearings)	**-V3**	**-55** (Round PCB)	**-56** (Round PCB)	Pinion 10/1
		-V6	**-57** (Round PCB)	**-58** (Round PCB)	Pinion 12/3, 12/5
		-V12	**-59** (Round PCB)	**-60** (Round PCB)	Pinion 12/4
			-83 (Round PCB)	**-82** (Round PCB)	Plain shaft for lead screw M2 - M2,5
			-31 (Solder tag PCB)	**-30** (Solder tag PCB)	Plain shaft, plain shaft for lead screw M3
			-35 (Solder tag PCB)	**-34** (Solder tag PCB)	Pinion 10/1
			-37 (Solder tag PCB)	**-36** (Solder tag PCB)	Pinion 12/3, 12/5
			-39 (Solder tag PCB)	**-38** (Solder tag PCB)	Pinion 12/4
			-53 (Solder tag PCB)	**-52** (Solder tag PCB)	Plain shaft for lead screw M2 - M2,5

For notes on technical data and lifetime performance refer to "Technical Information".
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Technical specs of FAULHABER RDM66200 are the following.

FAULHABER

Stepper Motors

Two Phase, 200 steps per revolution
PRECIstep® Technology

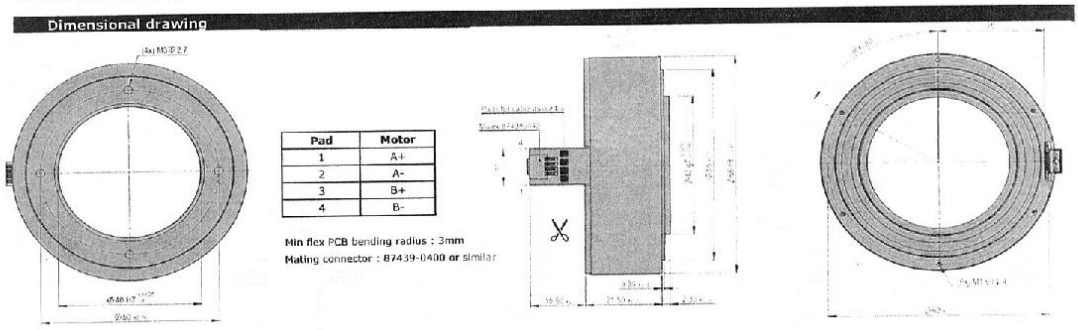
Preliminary Datasheet

200 mNm

RDM66200-A-01

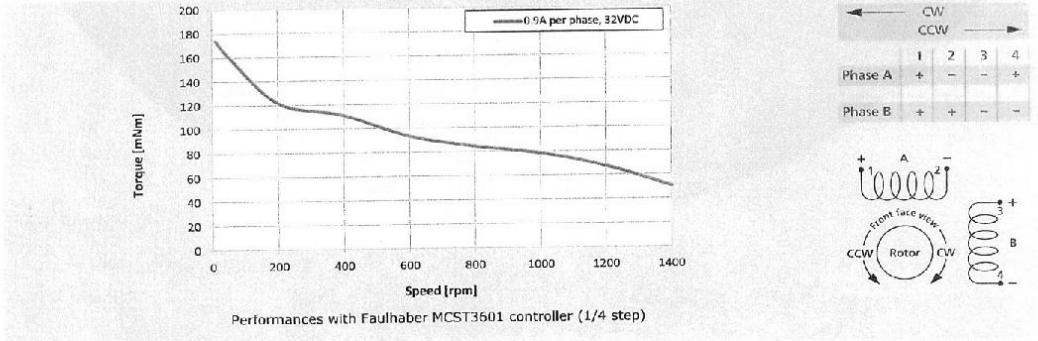
		A	
1	Nominal current per phase (both phases ON)	0.9	A
2	Phase resistance (at 20°C)	3.8	Ω
3	Phase inductance (1kHz)	2.2	mH
4	Back-EMF amplitude	3.8	V/k step/s
5	Holding torque (at nominal current in both phases)	200	mNm
6	Holding torque (at twice the nominal current)	350	mNm
7	Step angle (full step)	1.8	Degree
8	Angular accuracy (general tolerance)	± 5	% of full step
9	Residual torque, max	20	mNm
10	Rotor inertia	30	$\cdot 10^{-6}$kgm^2
11	Resonance frequency (at no load)	100	Hz
12	Electrical time constant	0.58	ms
13	Ambient temperature range	-20 ... +50	°C
14	Winding temperature tolerated, max.	130	°C
15	Thermal resistance R_{th1}/R_{th2}	1.36 / 6.94	°C/W
16	Thermal time constant τ_{th1}/τ_{th2}	16 / 1 000	s
17	Shaft bearings	Ball bearing, preloaded	
18	Shaft load, max :		
	- axial	30 (limited by ball bearing preload)	N
	- radial	300	N
19	Mass	210	g
20	Isolation test voltage	250	VDC

Dimensional drawing



Pad	Motor
1	A+
2	A-
3	B+
4	B-

Min flex PCB bending radius : 3mm
Mating connector : 87439-0400 or similar



Performances with Faulhaber MCST3601 controller (1/4 step)

For notes on technical data please refer to „Technical Information".

Below a 3D image of the ring motor.

Fig.4 – The ring laser motor. This motor is able to rotor over 360 degree.

The FAULHABER RDM66200 is an all-in-one device including gearbox mechanism but the other motor ADM1220S need to be mounted adding an appropriate gearbox. In accordance with torque and precision positioning requirements both ADM1220S are assembled with the "12/3" gearbox item. All Eye hand-piece motors are step motors; we required stepper motors because of great positioning precision is mandatory.

To simplify the motor control all selected motors are driven by the same type of control unit suggested by FAULHABER. The MCST 3601 is the chosen motor electronic driver.

Fig.5 – Two views of the MCST3601 motor driver unit.

Below the datasheet of MCST 3601

NEW

Motion Controller

1-Axis controller with microstepping,
USB interface and reference input

For combination with:
Stepper motors

Series MCST 3601

		MCST 3601	
Power supply	U_B	9 ... 36	V DC
PWM switching frequency	f_{PWM}	16 000	kHz
Max. continuous output current range [1]	I_{dauer}	0 ... 1,1	A
Max. peak output current	I_{max}	1,6	A
Max. current resolution		5	mA
Microstepping		up to 256 [2]	
Scanning rate (in full step mode)	N	30	µs
Inputs:			
– Digital, 24 VDC		3	
– Analog, 10 VDC		1	
Outputs:			
– Open drain, 24 VDC		6	
– +5 VDC, 100 mA		1	
Operating temperature range		– 30 ... + 70	°C
Mass		22	g

[1] at 22°C ambient temperature
[2] µstep/full step

Connection information			
Connections 1-6 :		digital input	
REF_L / DIR_IN	left stop switch input	programmable pull-up to +5V or direction input in S/D[4] operation mode	
REF_R / EN_IN	right stop switch input	programmable pull-up to +5V or enable input in S/D[4] operation mode	
HOME / STEP_IN	home switch input	programmable pull-up to +5V or step input in S/D[4] operation mode	
ENC_A / IN1	incremental encoder	channel A input or digital input 1	
ENC_B / IN2	incremental encoder	channel B input or digital input 2	
ENC_I / IN3	incremental encoder	index / null channel I input or digital input 3	
Connection 7 :		+5V output	
Current range		0 ... 100	mA
Connection 8, 13[2], 24 :		GND	
Signal ground			
Connection 9-12 :		motor A+, A-, B+, B-	
Output voltage		= U_B	VDC
Coil current range		0 ... 1,1	A
(depends on programmation and jumper settings)		0 ... 1,6 (Peak)	A
Connection 14[3] :		U_B	
Supply voltage range		9 ... 36	VDC
Connection 15-16 :		reserved	
Max speed rate transfer		1	Mbits/s
Max number of nodes		110	
Value of the termination resistors (2x)		120	Ohm
Connections 17-22 :		digital output	
Voltage range open drain outputs		= U_B	VDC
Current range open drain outputs		0 ... 100	mA
Connection 23 :		analog input	
Voltage range		0 ... 10	VDC

[3] Crossing the connections 13 and 14 may irreversibly damage the controller.
[4] S/D = step and direction (direct drive) mode.

For notes on technical data and lifetime performance refer to "Technical Information".
Edition 2015

Accessories

The MCST3601 is delivered with one USB cable and four spacer bolt.	Motor Type	Part No.
Adapter board (for flex board connection)	**FDM0620 p=0.5mm** **FDM0620 p=1mm**	0.9500.90.000

Features

The MCST3601 is a stepper motor controller that is mostly intended to be used as an evaluation board.
It has the capability to drive the full range of PRECIstep® stepper motors thanks to a selected current range.

This range must be selected manually through jumpers and programmed with the TMCL-IDE software.

The USB communication makes it fully programmable and the many inputs and outputs enable an external interaction.

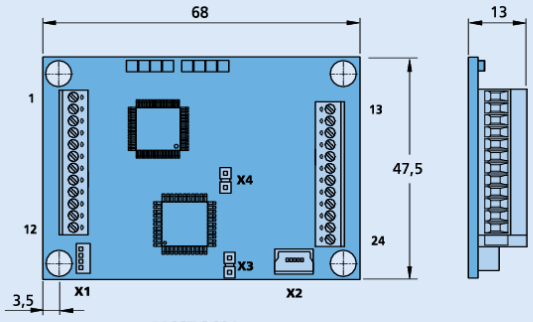
Full step or microstepping up to 256 can be managed by programming.

Moreover, the MCST3601 comprises screw terminals for quick setup and a Molex connector compatible with the standard cables solutions offered on PRECIstep® stepper motors.

Finally, the MCST3601 has the capability to read and treat an external input signal that may be sent by a sensor or an encoder. This is very useful in the case where a homing function must be made before starting the movement, in other words, when the motor is looking for a reference position before starting.
Note that this function is not acting like a closed loop regulator.

Dimensional drawing and connection information MCST 3601

Scale reduced



MCST 3601

Motor connection

No.	Function
1	REF_L / DIR_IN
2	REF_R / EN_IN
3	HOME / STEP_IN
4	ENC_A / IN1
5	ENC_B / IN2
6	ENC_I / IN3
7	+5VOUT / 100mA
8	GND
9	Motor A+
10	Motor A-
11	Motor B+
12	Motor B-

X1 Motor connector

Connector housing:
Molex 51021-0400
Contacts: Molex 50079-8000
Wire: AWG 26-28

Supply connection

No.	Function
13	GND
14	U_B
15	reserved
16	reserved
17	OUT0
18	OUT1
19	OUT2
20	OUT3
21	OUT4
22	OUT5
23	IN0
24	GND

X2 USB 2.0 (12Mbit/s)

Any standard mini-USB plug compatible with Molex 500075-1517

X3, X4 Jumpers for current settings

For notes on technical data and lifetime performance refer to "Technical Information".
Edition 2015

We use 3 MCST3601, one for each motor. The MCST3601 is equipped with a micro controller and a driver, it can precisely regulate phase currents from 10 mA to 1.1 A. At the same time, it can be operated with a supply voltage that can vary between 9 and 36 VDC. Thanks to simple and fast communication with a PC via USB 2.0, all types of movements can be programmed using the available software. In the context of LA-ROSES experiment we develop a specific set of SW routines to program these drivers in order to provide basic functionalities to fine control a single movement type. The LA-ROSES high-level control system will use specific calls to these last low-level routines so that to realize synchronous motion as to follow the marked welding path by the laser spot. The MCST3601 provide also 10 I/O lines to allow external variables to be taken into consideration such as mechanical stops. Furthermore, the MCST 3601 can actuate stepper motors in micro stepping mode. In this operating mode, up to 256 micro steps can be programmed per full step. This allows the resolution of the controlled (rotary or linear) movement to be increased considerably and/or the vibrations caused by the motor to be reduced. This

capability fits well LA-ROSES movement requirements where resolutions have to be considered in the micro meter range.

Follows the scheme of the electrical connections between each motor and its MCST 3601 control unit.

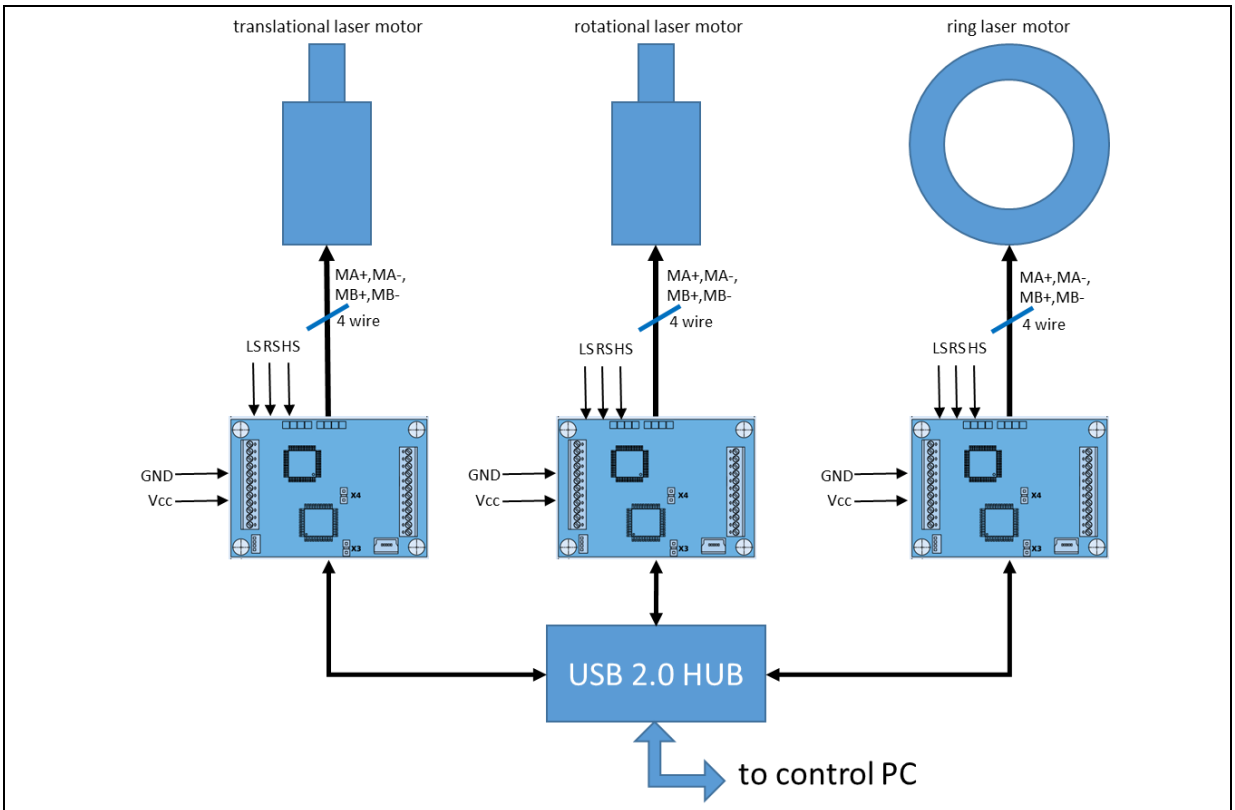


Fig.6 – Two views of the MCST3601 motor driver unit.

LS, RS and HS are Left Stop switch, Right Stop switch and Home stop switch; they are physical connections between the mechanical microswitches stops and the matching control input pin. MA+,MA-,MB+ and MB- are the physical connections between the motor phases and the corresponding control outputs. The LA-ROSES high level control system will communicate with the Eye hand-piece control unit sending specific movement command, and receiving information about positioning data and system status, to (from) the actual MCST 3601 unit via an external USB HUB.

1.2 Laser unit

The selection of the laser unit to be mounted on the Eye hand-piece has been difficult because we required to match all laser characteristics similar to the laser system described in D2.1, where a fiberoptic laser was used by the surgeon, and at the same time we required to be able to manipulate the laser as it can be driven along a circular path. The main issues we had to solve were:

1. The fiberoptic manipulation. It is well known that fiberoptic cables must be manipulated with great care and it is no possible to roll it so that it can be arranged along a sharp circular path as we required.
2. Current fiberoptics used in manual laser corneal welding need to be sterilized because it must be handled by the surgeon. We required to design a laser handling system so that it was not necessary to sterilize any components of it. This is a very important feature to be accomplished in order to simplify the medical certification of such handling system.

Taking into account these requirements after having checked a lot of laser systems we selected the Osela streamline laser provided by LASER 2000 GmbH company. In particular we choose the SL-810-500-TV-D configuration because it can be arranged having a separate power driving unit as FIG. 7 shows.

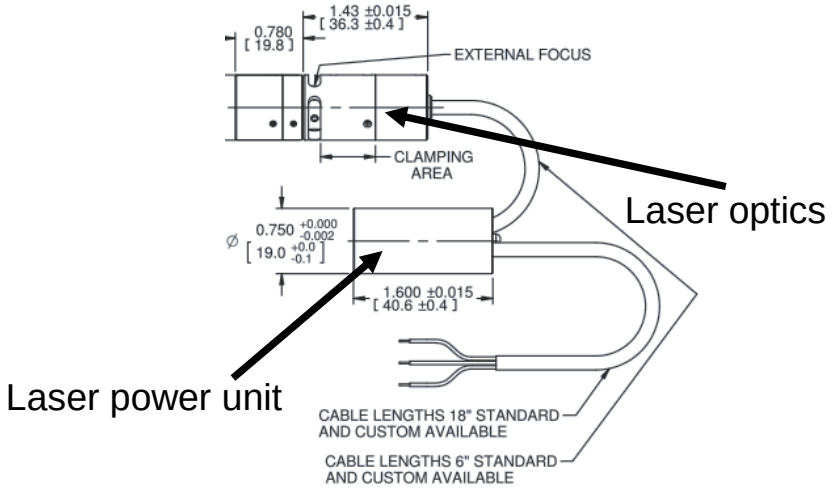


Fig.7 – The OSEL streamline laser system. The chosen configuration consists of a separate unit as powering source. The laser optics/tip is hold by the laser handling system.

This configuration allows the laser optics to be attached to the ring motor as it is set free to rotate without cable problems. Furthermore the laser optics can be mounted and manipulated by mechanical handling system we designed so that it does not required to be manipulated by hand by the surgeon avoiding any sterilization needs.

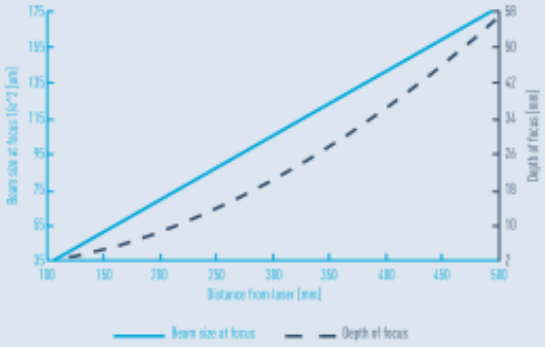
During ex-vivo test, we will have to perform, we will need to control the laser power output in the range of 50mW-90mW; the streamline laser can be CW modulated by an external 0 to 5v external signal and also it can be used in pulsed mode. Below the streamline laser datasheet

LASER DIODE MODELS AND FOCUSING OPTIONS

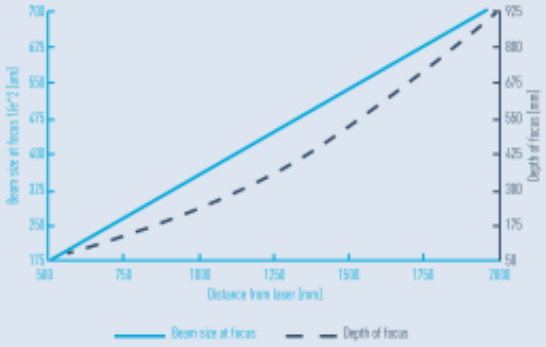
At Osela we provide many different focusing options giving you the flexibility to choose the one that best suits your application. The Streamline laser is free focusable externally without removing any optics. From the graphs below, note the beam size and Depth of Focus (DOF) values and then multiply by the K constants for the laser diode model and focus option of choice (A, B, C, D or E).

Example: From the graphs at 400 mm working distance, Focus = 140µm, DOF = 36 mm. Than for Laser Model 660 nm 130 mW the line thickness at focus for OPTION A will be 212um (i.e.140 um x 1.52). Its depth of focus will be 88.92mm (i.e. 36mm x 2.47).

SHORT RANGE



LONG RANGE



DIODE MODEL				FOCUSING & DOF OPTIONS AND CONSTANT									
WAVELENGTH (nm)	DIODE POWER (mW)	WAVELEGNTH TOLERENCE (nm)	OPERATING CURRENT[2] (mA)	A		B		C		D		E	
				K_{focus}	K_{DOF}	K_{focus}	K_{DOF}	K_{focus}	K_{DOF}	K_{focus}	K_{DOF}	K_{focus}	K_{DOF}
405[1]	35	+5/-5	50	0.68	0.80	1.65	4.74	0.28	0.13	0.98	1.69	2.39	10.00
	100	+10/-5	70	0.64	0.72	1.46	3.74	0.26	0.12	0.93	1.52	2.12	7.88
450[1]	100	+10/-10	100	0.66	0.69	1.95	6.00	0.37	0.22	0.96	1.45	2.83	12.65
520[1]	50	+10/-5	145	0.74	0.75	2.80	10.77	0.41	0.24	1.07	1.58	4.06	22.69
635	5	+5/-5	50	0.79	0.70	2.58	7.44	0.45	0.22	1.15	1.47	3.75	15.67
	10	+8/-4	60	0.96	1.02	2.58	7.44	0.54	0.32	1.39	2.15	3.75	15.67
640	25	+3/-10	90	0.96	1.02	2.29	5.86	0.54	0.32	1.39	2.15	3.33	12.35
	45, 80	+5/-5	120, 185	0.96	1.02	2.06	4.73	0.54	0.32	1.39	2.15	2.99	9.98
	150	+3/-8	185	0.65	0.47	1.88	3.93	0.37	0.15	0.94	0.99	2.74	8.28
650	5	+10/-5	48	0.73	0.56	2.38	6.09	0.41	0.18	1.05	1.19	3.46	12.84
	10	+10/-5	55	0.73	0.56	2.26	5.46	0.41	0.18	1.05	1.19	3.27	11.51
660	35	+5/-10	100	0.95	0.96	2.52	6.84	0.53	0.30	1.37	2.02	3.66	14.41
	50, 100	+5/-5	125,175	1.52	2.47	2.14	4.92	0.85	0.41	2.20	5.22	3.11	10.37
	130	+5/-5	200	1.52	2.47	2.14	4.92	0.85	0.41	2.20	5.22	3.11	10.37
690	35	+5/-10	95	1.15	1.36	2.62	7.10	0.47	0.23	1.66	2.87	3.80	14.96
	50	+10/-10	150	1.09	1.22	2.11	4.63	0.44	0.20	1.58	2.57	3.07	9.75
785	75, 120	+10/-10	150, 200	1.57	2.23	2.83	7.25	0.64	0.37	2.28	4.71	4.11	15.27
810	150	-0.6	230	1.52	2.03	3.29	9.46	0.62	0.34	2.21	4.27	4.77	19.94
830	50, 100	+10/-10	115, 135	1.19	1.21	3.00	7.66	0.67	0.38	1.73	16.14	4.35	16.14
	200	+10/-10	240	1.03	0.91	3.37	9.72	0.58	0.29	1.50	1.93	4.90	20.48

[1] 9 to 30V operation

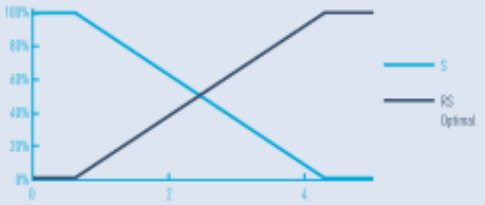
[2] Measured at 25°C at operating voltage of 5V for ≥635nm and 12V for 405, 450 and 520nm models)

MODULATION

The Streamline laser can be modulated by an external 0 to 5V external signal through the white wire. The **S type** modulation is included by default with the Streamline Module.

FUNCTION	CODE	ON	OFF
TTL	T	0 to 2V	3 to 5V
Reverse TTL	RT	3 to 5V	0 to 2V

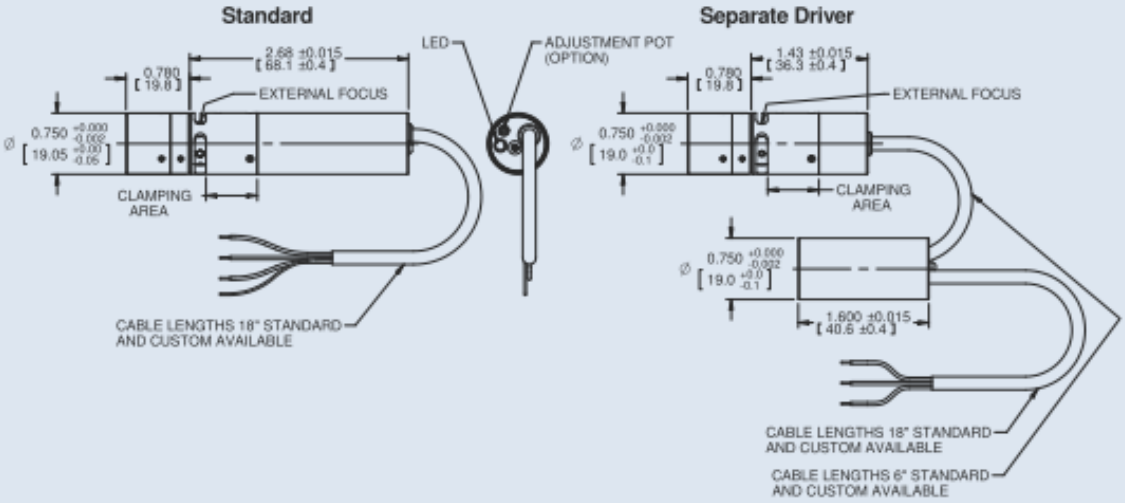
Note: One modulation input needs to be selected, S (default), RS, T or RT



SPECIFICATIONS

Bore sight (mrad)	< 3 mrad
Wavelength Drift	≈ 0.25 nm/ degC
Pointing Stability	< 6 µrad/°C
Modulation Rise/Fall time	< 5µ sec, 100% modulation depth (10 Kohm input impedance)
Protections (Built in)	ESD, Over voltage (up to 30 VDC), Over-temp Shutoff (> 50 deg C)
Long term Power stability (8 hours)	< 3 %, 2 minute warm up time
Operating Voltage	5 ± 0.5VDC, 4.5 to 30V Optional (9-30V for < 635 nm)
Working Temp Range	-10 to to +50 °C (housing)
Weight	< 50 g
Power Supply Cable	18 inches 3 conductors Belden 9533, with flying leads
ESD Protection	Level 4
Shock Tolerance	30g, 6ms, functional

MECHANICAL SPECIFICATIONS



STREAMLINE SINGLE LINE GENERATOR

FIG 1 - INTENSITY DISTRIBUTION ALONG THE LINE

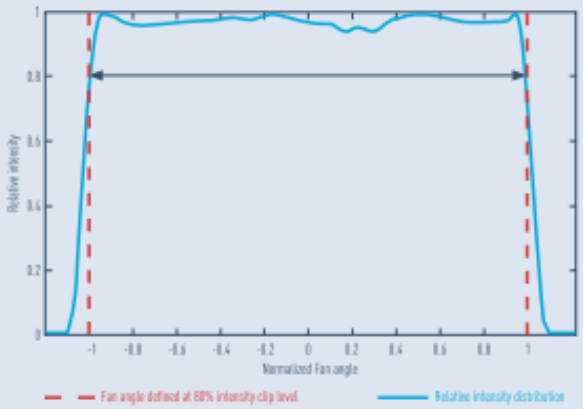
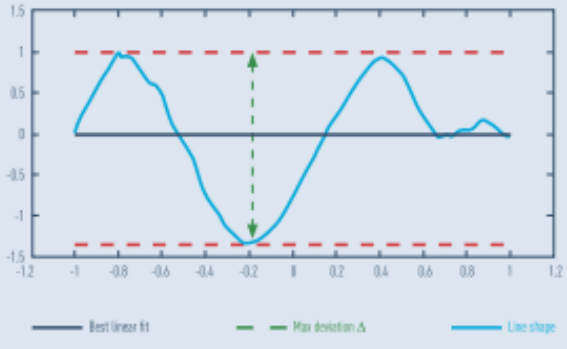


FIG 2 - LINE STRAIGHTNESS



SPECIFICATIONS

SPECIFICATIONS		VALUES
Uniformity (line intensity distribution along the line)[2]	$\frac{Imax - Imin}{Imax + Imin}$	20% (typical) ≤7.5%[1]
Relative intensity clip that define the fan angle		80%
Contained energy In the fan angle	$\frac{\text{Energy in fan angle}}{\text{total energy}}$	≥95%
Line Straightness (deviation from the best linear fit)[2]	$\frac{\Delta}{L \text{ (line lenght)}}$	≤0.1% ≤0.05%[1]
Fan angle		1 to 90° [3]
Fan angle tolerance (line diverging angle from the tip of the laser)		+1.0/-0.5° (FA <30 °)
		+1.5/-0.5° (FA ≥30°)

[1] For SL *Plus* (see Streamline *PLUS* datasheet).
[2] Uniformity and straightness are measured at 80% of the fan angle (100% for SL *Plus*).
[3] Available Fan Angle (°) 1, 5, 10, 15, 20, 30, 38, 45, 60, 75, 90 custom upon demand.

ORDERING CODE

SL	-	XXX Wavelength	-	XXX Diode Power	-	X Electronic	X Focusing Option	-	XX Fan Angle	-	XXX-XX Multi beams	-	XXXXX Option
		see table		see table		S	A		1, 5, 10		(Optional)		SD
						RS	B		15, 20		Refer to the		24V
						T	C		30, 38		Multi-dots and		
						RT	D		45, 60		Multi-Lines		
							E		75, 90		page		

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